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13. ABSTRACT (Maximum 200 words)

Theoretical and experimental studies of the Grating Coupled Oscillator (GCO) indicate a three-wave interaction. Beating between the waves is observed in the sub-threshold radiant power with a cube root dependence on the current. Both gain and loss are greater than predicted. Observed parametric power dependence necessitated development of a self-consistent field theory.

The Grating Horn resonator magnified GCO intensity by 100 times. Many orders of magnitude further increase in power are predicted with the novel Lossless Resonator concept.

GCO and Smith-Purcell experiments with moderate and high energy electron beams corroborate the underlying GCO theory.

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# FINAL PROGRESS REPORT

ARO Grant # DAAD19-99-1-0067 (39172-PH)

# A New Tunable Source for the FIR-THz Spectral Region

For the period March 1, 1999 – Feb. 28, 2003

J. Hayden Brownell
June 26, 2003

(4) Statement of the problem studied:

The Grating Coupled Oscillator (GCO), first demonstrated by this group in 1997, has the potential to be a practical coherent source for far-infrared/terahertz (FIR/THz) research and applications. The GCO, simply an electron beam skimming a diffraction grating, has inherently many desirable features: continuously tunable from microwave to visible, continuous wave at room temperature, excellent spatial and spectral quality, stable, compact, robust, simple, and economical. Alternative sources, e.g. solid-state, short-pulse optical switches, free-electron lasers, and blackbody, do not share these characteristics.

The GCO emits radiation by the Smith-Purcell effect: diffraction of the electron wake field. Spontaneous Smith-Purcell emission is easily generated. The difficulty lies in developing enough feedback in an open resonator (i.e. the grating) to produce sufficient coherent power without resorting to an enclosed resonator cavity, thereby limiting the tuning range. Closure enhances feedback by confining the operating spectrum. The Backward-Wave Oscillator and the Orotron are closed-resonator cousins of the GCO that operate well at lower frequencies but not above 1 THz. The aim of this project was to understand the beam-wave gain process, though parametric studies, in enough detail to pinpoint optimum resonator designs by which the GCO could operate well into the terahertz regime.

(5) Summary of the most important results:

In the second year of this project, the PI John Walsh died suddenly due to complications from a broken ankle. I assumed leadership of his group at this time but the shock and loss of Prof. Walsh's knowledge severely disrupted progress. Roughly a year passed before I felt we were making substantial headway again. Thankfully, I now feel we have made very significant leaps toward our goal in the last two years, surpassing my expectations. One consequence of Prof. Walsh's death was a reduction in operating expenses so that the originally three year project could be extended to four.

The project involved a four-pronged strategy for developing the GCO: Experiments with and theoretical modeling of (a) low energy GCOs, (b) moderate energy GCO gain and Smith-Purcell radiation, (c) high energy Smith-Purcell radiation, and (d) low energy dielectric resonators. A summary of significant results follows.

(a) The primary focus is a low energy device based on a modified scanning electron microscope (SEM). The SEM provides a very high quality electron beam at a few tens of kilovolts. We observed super-radiant (i.e. the onset of laser) emission first in this apparatus in 1997, though this came somewhat as a pleasant surprise. At the time, estimates for the laser threshold were far from certain and tended to be substantially higher. Such a low observed threshold cast doubt on our model of the interaction driving the output. Subsequent experiments have focused on distinguishing characteristics that can identify the actual process involved.

One such characteristic was a curious wiggle in the emitted power that would appear sporadically just below the threshold (Fig. 1). After completely replacing of the original SEM electronics with computer controlled circuitry, implemented in 2000, the operating conditions in the interaction region were stable enough to conclude that these wiggles are fundamental to the gain process, not just experimental artifacts. Parametric studies conducted in 2001 carefully mapped the dependence of the wiggle features on the electron energy.

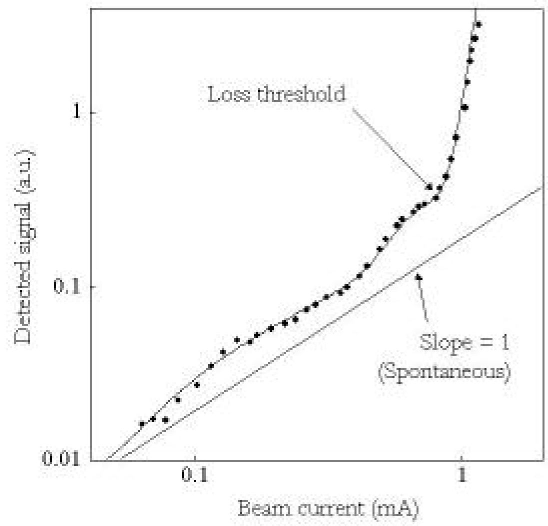


Figure 1: Detected SP-FEL power shown with the theoretical fit. The emission is greater than spontaneous indicating that losses are suppressing growth well below the identified threshold.

Even with the vast improvement of the stability in device performance, by far our more significant progress is in developing a theoretical model that fits the observed power. This model is by no means complete, still only a one-dimensional approximation and dependent on a number of free parameters, yet the agreement is beyond doubt (theoretical fit to data shown as solid lines in Figs. 1 and 2). The process relies on the coherent superposition of three electromagnetic waves simultaneously coupling with the electron beam. This model was proposed fifty years ago for traveling wave tubes [1] but the existence of three waves had not been demonstrated and its application to an open resonator debatable. In effect, we observed coherent beating of these three fundamental modes in the so-called quantum regime! [2]

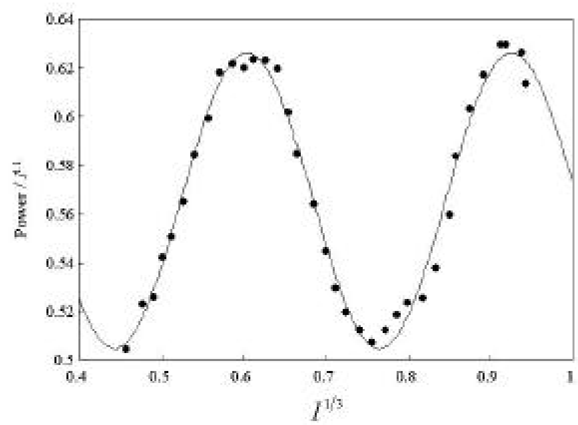


Figure 2: Normalized sub-threshold power vs. $I^{1/3}$ fit to Cosine, verifying a three-wave interaction.

The fit to the power has resolved some questions and, not surprisingly, raised new ones. The values of the free parameters implied by the fit highlight the avenues most likely to yield increased gain and, thereby, ultimate power and spectral range. Both the gain and loss are significantly higher than we had anticipated. To reconcile these questions, we developed more realistic theoretical model self-consistently incorporating grating dispersion, beam waist parameters, and loss. In addition, we mapped experimentally the output power dependence of the many other influential parameters defining the operating conditions, such as electron beam spot size and divergence, beam approach angle relative to the grating surface, grating length and profile. This parameter space is too large to cover, though patterns have emerged. Most significant, the three-wave oscillations are robust and appear in all conditions, implying that the interaction is fundamentally stable against fluctuations. We also find that nearly all of the parameters studied are interdependent, precluding a simplified theory. And while the predicted scaling laws generally hold true,

discrepancies remain that suggest a full three dimensional theory may be necessary to explain them. A report on these conclusions is in preparation.

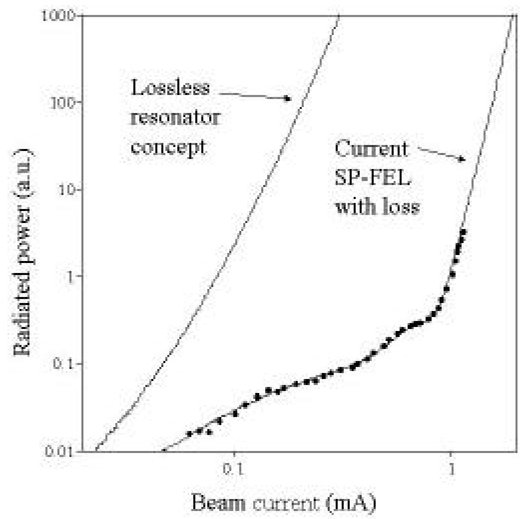


Figure 3: Comparison of the SP-FEL power, as currently implemented, and that from the envisioned "lossless resonator" SP-FEL.

Through the process of deriving this theory and analyzing the parametric data, it became apparent that the loss was severely limiting GCO performance and that, far from being negligible, the output Smith-Purcell radiation was the dominant source of loss. It is paramount for GCO success that the loss be quenched, yet the signal should not be eliminated either. A novel resonator design dubbed, the "lossless resonator", achieves this result without additional feedback elements, which I have argued would negate several advantages of the GCO. Figure 3 compares the radiant power predicted from the lossless resonator to that detected from the standard GCO (shown in Figure 1) for the same beam parameters. The lossless resonator surpasses the current standard by many orders of magnitude at a fraction of the current. In short, a successful lossless resonator GCO would satisfy the criterion for a practical THz source. A description of the lossless resonator concept is in preparation.

The second major advance in GCO performance followed from the notion that folding the grating about the beam would be tantamount to spreading the beam thinly over the grating. The latter is very difficult to accomplish. The grating horn (GH, shown in Fig. 4b) joins two planar gratings at an acute angle. The beam passes along its vertex and reacts to a more intense local field than the simple planar case. As a result, the GH produces one hundred times more detectable power than the standard planar

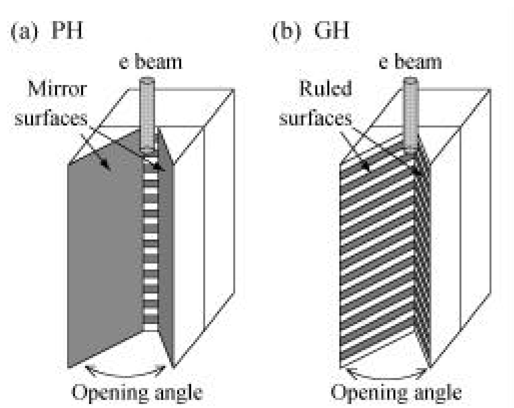


Figure 4: Two alternative resonator designs tested: (a) Planar horn and (b) Grating horn.

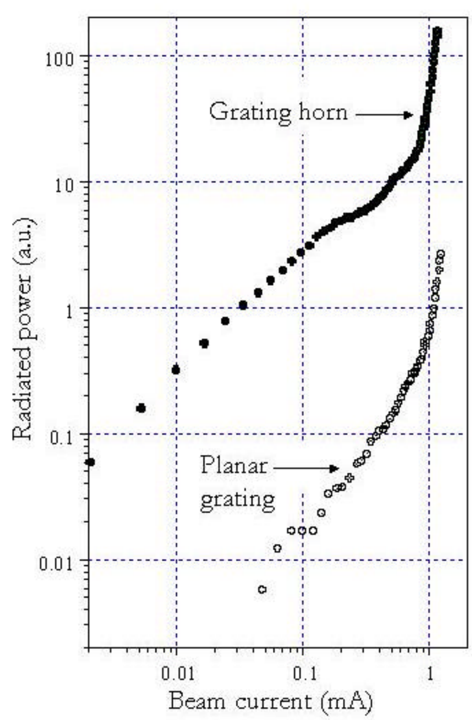


Figure 5: Detected SP-FEL power from the grating horn (GH) and a planar grating, taken sequentially for accurate comparison.

grating (Fig. 5). Additionally, as verified by testing the planar horn (PH, shown in Fig. 4a), the horn geometry condenses and collimates the emission into a well defined light beam.

(b) The second prong of our strategy was initiated in 2001 to investigate the viability of grating based laser resonators driven with a moderately high energy, pulsed electron beam. This work was done in collaboration with the free-electron laser group at ENEA, Frascati, Italy, in their 2.3 MeV accelerator facility. Both a spontaneous Smith-Purcell experiment and gain studies with an enclosed GCO were completed.

Results from the former experiment indicated clearly the picosecond temporal profile of the electron bunch. This study is a significant test of theory as well as of the S-P interaction as a practical, non-invasive diagnostic for future particle accelerators. Data from the second study agree very well with theoretical predictions based on the low energy model developed for this experiment. The most significant conclusion is that grating, dielectric slab, and magnetic wiggler resonators all produce comparable spontaneous and stimulated emission when driven by the same beam. But, grating resonators produce higher frequencies for a given beam, afford greater spectral control, and are far simpler to manufacture. Therefore, by its reduced dependence on high energy accelerators, a grating based free-electron laser offers a reasonably attractive alternative to the traditional wiggler-type FIR/THz FEL. A report of these results is in preparation.

(c) The third experiment is an ongoing effort in collaboration with Brookhaven National Laboratory at the Accelerator Test Facility (ATF). We are looking for Smith-Purcell radiation at very high (50 MeV) beam energy to confirm a variety of predictions when our model is applied to this extreme case. The nature of the coupling between the electrons and the diffracted wave requires that the electrons remain near the grating surface. For technological and scientific reasons, this experiment was designed at the limit of the focusing ability of the ATF accelerator. While we observed a clear signal consistent with SP radiation during one run with particular fine focusing in 2000, relatively poor beam focusing since has prevented us from reproducing this result. We reported these findings at the 11$^{th}$ ATF User's Meeting. An upgrade of the apparatus is in progress to overcome dispersion instabilities in the beam causing the focusing problems.

(d) In our fourth project, we have studied theoretically the advantages of employing a dielectric waveguide resonator with the scanning electron microscope. The results indicate that high order emission should exhibit substantial gain. This is significant because machining techniques impose practical limitations on the minimum size of the resonator. Achieving high order emission would allow high frequency generation with a relatively large and easily manufactured resonator. These conclusions are being tested in experiments initiated at the end of 2001. To date, transitory signatures of coherent feedback have been seen but various effects, primarily thermal damage to the dielectric surface, appear to be preventing repeatable measurements. Steps to avoid these impediments are underway. When successful, this experiment can be compared with the GCO to identify susceptibilities particular to both cases.

The program summarized above differs in several respects from the proposed plan, though it adhered to the essence. The power growth curves measured in the initial stages with the low energy GCO puzzled us greatly and demanded our focus. Clearly, our understanding of the interaction was incomplete and the correct interpretation proved to be quite subtle. The Pierce

three-wave theory derived fifty years ago yields an intuitive result [1], which we have utilized to glean basic scaling laws, but is too simple to model the GCO. Instead, a fully self-consistent field description, including loss, must be employed to appreciate parameter dependences that arguably should be secondary yet we observe to be strong.

Armed with this knowledge and the corroborating evidence from our other experiments, the path to efficient GCO performance is becoming clearer. This insight led directly to the grating horn resonator and the lossless resonator concepts. Together they will likely drive the GCO to saturation, predicted to be on the order of 10 milliwatts narrow band, with easily manageable beam power, over a much broader spectral range than has been demonstrated thus far.

From the great advance and added confidence in our understanding of the GCO leading to novel designs, I believe we have fulfilled and surpassed the original proposal objectives.

(6) List of publications:

<u>Refereed Journals</u>:


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2. I.J. Owens and J.H. Brownell, “High-order gain in a beam driven dielectric resonator,” Phys. Rev. E **67**, 036611 (2003).

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11. J. E. Walsh, J. H. Brownell, J. C. Swartz, and M. F. Kimmitt, "Coherent Tunable FIR Source," Terahertz Spectroscopy and Applications, M.S. Sherwin ed., SPIE **3617** (1999) 192.

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1. Arash Bakhtyari, *Gain Mechanism in a Compact Smith-Purcell Terahertz Source*, PhD (September, 2002).

2. Israel Owens, *Gain calculation for a Cerenkov Thin Film Free Electron Laser*, MS (June 2000).

3. Yeechi Chen, *Quantum mechanical theory for gain in Cerenkov Free Electron Lasers*, BA (June 2000).

4. Thomas Harris, *A Smith-Purcell LINAC*, BA (June 2000).

5. Gunnar Stolze, *A New Polarizing Interferometer for Far Infrared Spectroscopy*, MS (June 1999).

6. James McGuire, *The Excitation of Surface Modes, A Novel Application of Total Internal Reflection*, BA (June 1999).

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1. J.H. Brownell, H.L. Andrews, A. Bakhtyari, and M.F. Kimmitt, "Progress in microFEL development," THz-Bridge Workshop, September 2002.

2. H.L. Andrews and J.H. Brownell, "Compact, medium energy, grating-based THz source," THz-Bridge Workshop, September 2002.

3. I.J. Owens and J.H. Brownell, "High-order generation in a Cerenkov FEL," 24th International Free Electron Laser Conference, September 2002.

4. Bakhtyari, J.E. Walsh, J.H. Brownell, “Gain in a Compact, Tunable Terahertz Laser,” CLEO / QELS 2002, May 2002.

5. Arash Bakhtyari, John E. Walsh, J. Hayden Brownell, “Oscillation in FEL Self-Amplified Spontaneous Emission,” APS April Meeting 2002.

6. Progress in the BNL-ATF Smith-Purcell experiment, J.H. Brownell, R. Fernow, H. Kirk, V. Yakimenko, presented at the 11th ATF User’s Meeting (January, 2002).

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1. A New Source of THz-FIR Radiation, J. E. Walsh, J. H. Brownell, J. C. Swartz, and M. F. Kimmitt, IEEE LEOS Newsletter **13** (1999) 11.

2. Free Electron Laser for the Far Infrared, David Pope in The Industrial Physicist, (February 1999) 18.

3. Technology Briefs in Photonics Spectra (August 1999) 44.

(7) List of all participating scientific personnel:

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Dr. J.C. Swartz (Research Associate)
Dr. S. Trotz (Research Associate)
Gunnar Stolze (MS, 1999)
Arash Bakhtyari (PhD, 2002)
Heather Andrews (PhD candidate, expected June 2003)
Israel Owens (PhD candidate, MS in 2000)

(8) Report on inventions:

A provisional patent has been applied for the Grating Horn invention.

(9) References:

[1] J. R. Pierce, *Traveling-Wave Tubes* (D. Van Nostrand Company, Inc., New York, 1950).

[2] Friedman, A. et al., "Spontaneous and stimulated emission from quasifree electrons," Reviews of Modern Physics 60, 471 (1988).